

# Charged Higgs boson production in single top mode at the LHC

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**Abstract.** The main production mode for a light charged Higgs boson at the LHC is  $pp \rightarrow t\bar{t}$ , with one the top-quarks decaying to a charged Higgs and a  $b$ -quark. However, single top production also gives rise to final states with charged Higgs bosons. In this work we analyse how the two processes compare at the LHC@14TeV. We will be working in the framework of the two-Higgs double model, considering both a CP-conserving and a CP-violating version of the model. We conclude that the single top mode could help to constrain the parameter space in several versions of the model. We also discuss the role of other complementary production processes in future searches at the LHC.

## 1. Introduction

The discovery of a charged Higgs boson at CERN's Large Hadron Collider would be an unequivocal sign of physics beyond the Standard Model (SM). A light charged Higgs is well within reach of the LHC@8TeV in many Beyond the SM (BSM) models. Searches based on  $pp \rightarrow t\bar{t} \rightarrow bW^+\bar{b}H^-$  are currently being performed by both the ATLAS [1] and CMS [2] collaborations. A large portion of the parameter space with a light charged Higgs boson (below 150 GeV) has already been excluded by the two experiments in models with two Higgs doublets and in particular in the Minimal Supersymmetric Standard Model (MSSM). However, it is clear that even for a charged Higgs mass below the top-quark mass, the entire parameter space will not be ruled out when all the 8 TeV data is finally analysed. Hence, one may ask if by the end of the 13-14 TeV run a light charged Higgs boson will be either found or definitely excluded and if so in which models? The answer to that question is highly dependent on the model being scrutinised. It is expectable that most of the parameter space with a charged Higgs mass below the top mass will be probed for the MSSM as well as for other multi-Higgs extensions of the SM. It is clear though, that some multi-Higgs versions will not be probed in their entire parameter space range even for a light charged Higgs. For those particular scenarios it is useful to consider all charged Higgs production process as to maximize the discovery potential. As the single top production cross section is about one third of the  $t\bar{t}$  one, it could in principle slightly boost the chances of finding or indeed disproving the existence of a light charged Higgs boson. The

purpose of this work is to show that a slight improvement can be obtained by complementing the present search, based on the  $t\bar{t}$  mode, with the search in the single top mode.

## 2. Two-Higgs doublet models

The softly broken  $Z_2$  symmetric ( $\Phi_1 \rightarrow \Phi_1$ ,  $\Phi_2 \rightarrow -\Phi_2$ ) two-Higgs doublet model (2HDM) potential can be written as

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] ,$$

where  $\Phi_i$ ,  $i = 1, 2$  are complex SU(2) doublets. Hermiticity of the potential forces all parameters except  $m_{12}^2$  and  $\lambda_5$  to be real. Then, the nature of  $m_{12}^2$  and  $\lambda_5$ , together with the chosen vacuum configuration, will determine the CP nature of the model (see [3] for a review). If CP is conserved we end up with two CP-even Higgs states,  $h$  and  $H$ , and one CP-odd state,  $A$ . If CP is broken, the three spinless neutral states with undefined CP quantum number are usually denoted by  $h_1$ ,  $h_2$  and  $h_3$ . However, as long as the vacuum configuration does not break electric charge, which was shown to be possible in any 2HDM [4], there are in any case two charged Higgs boson states, one charged conjugated to the other.

In this work we will focus on two specific realisations of 2HDMs, one CP-conserving and the other explicitly CP-violating [5, 6]. In the CP-violating version  $m_{12}^2$  and  $\lambda_5$  are complex and the fields' vacuum expectation values (VEVs) are real. Existence of a stationary point requires  $\text{Im}(\lambda_5) = v_1 v_2 \text{Im}(m_{12}^2)$ . Because the VEVs are real in both models, a common definition for the rotation angle in the charged sector  $\tan \beta = v_2/v_1$  can be used. Extending the  $Z_2$  symmetry to the Yukawa sector we end up with four independent 2HDMs, the well known [7, 8] Type I (only  $\phi_2$  couples to all fermions), Type II ( $\phi_2$  couples to up-type quarks and  $\phi_1$  couples to down-type quarks and leptons), Type Y or III ( $\phi_2$  couples to up-type quarks and to leptons and  $\phi_1$  couples to down-type quarks) and Type X or IV ( $\phi_2$  couples to all quarks and  $\phi_1$  couples to leptons) (details and couplings can be found in [9]).

We will now very briefly discuss the main experimental constraints affecting the 2HDM parameter space. The signal in our analysis originates from single top production with the subsequent decay  $t \rightarrow bH^\pm \rightarrow b\tau\nu$ . Hence, only the charged Higgs Yukawa couplings are present and therefore the only parameters we need to be concerned with are  $\tan \beta$  and the charged Higgs mass. Values of  $\tan \beta$  smaller than  $O(1)$  together with a charged Higgs with a mass below  $O(100 \text{ GeV})$  are both disallowed by the constraints [10] coming from  $R_b$ , from  $B_q \bar{B}_q$  mixing and from  $B \rightarrow X_s \gamma$  for all models. Furthermore, data from  $B \rightarrow X_s \gamma$  [11] imposes a lower limit of  $m_{H^\pm} \gtrsim 360 \text{ GeV}$ , but only for models Type II and Type Y. The LEP experiments have set a lower limit on the mass of the charged Higgs boson of 80 GeV at 95% C.L., assuming  $BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c \bar{s}) + BR(H^+ \rightarrow A W^+) = 1$  [12]. The bound is increased to 94 GeV if  $BR(H^+ \rightarrow \tau^+ \nu) = 1$  [12]. These bounds led us to take  $m_{H^\pm} > 90 \text{ GeV}$  and  $\tan \beta > 1$  for Type I and X. We will also present results for model Type II, where the bounds on the charged Higgs mass can be evaded due to the presence of new particles as is the case of the MSSM. The usual theoretical bounds such as the ones coming from requiring boundness from below of the potential and the ones from requiring perturbative unitarity are in this case redundant (same is true for the precision electroweak constraints).

## 3. Results and discussion

As previously discussed,  $pp \rightarrow t\bar{t}$  is the best process to search for a light charged Higgs boson at the LHC. However, because the single top production cross section is about one third of  $\sigma_{pp \rightarrow t\bar{t}}$ , it deserves a full investigation regarding its contribution to the production of charged

Higgs bosons. The signal consists mainly of a light charged Higgs boson produced via the  $t$ -channel process  $pp \rightarrow tj \rightarrow H^+ \bar{b}j$  (together with its charge conjugate), with the subsequent decay  $H^+ \rightarrow \tau^+ \nu$ , where  $j$  represents a light-quark jet. In what follows we are considering proton-proton collisions at a center-of-mass (CM) energy of  $\sqrt{s} = 14$  TeV and a top-quark mass  $m_t = 173$  GeV. We consider a charged Higgs boson mass interval of 90 to 160 GeV and the analysis is performed in 10 GeV mass steps.

Maximising the signal-to-background significance ( $S/\sqrt{B}$ ) makes both the  $s$ -channel and the  $tW$  single-top production modes negligible - only the  $t$ -channel process survives the set of cuts imposed. Signal events were generated with POWHEG [13] at NLO with the CTEQ6.6M [14] PDFs. The top was then decayed in PYTHIA [15]. We have considered only the leptonic decays of the tau-leptons, that is, the signal final state is  $pp \rightarrow lbj \cancel{E}$ , where  $l = e, \mu$  (electrons and muons) while  $\cancel{E}$  means missing (transverse) energy.

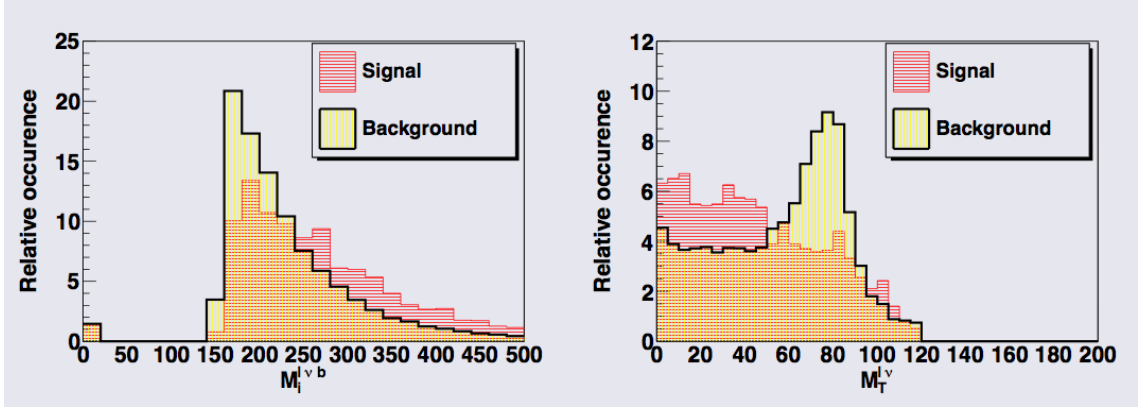
The irreducible background, single-top production with the subsequent decay  $t \rightarrow bW^+$ , was also generated with POWHEG. The main contributions to the reducible background are:  $t\bar{t}$  production,  $W^\pm + \text{jets}$  (including not only light quarks and gluons, but also  $c$ - and  $b$ -quarks) and the pure QCD background ( $jjj$ , where  $j$  is any jet). The  $t\bar{t}$  background was generated with POWHEG while  $W^\pm + \text{jets}$  (1, 2 and 3 jets) was generated with AlpGen [16]. Finally, the QCD background was generated with CalcHEP [17] (with CTEQ6.6M PDFs). The hadronisation was performed with PYTHIA 6. After hadronisation, DELPHES [18] was used to simulate the detector effects. For the detector and trigger configurations, we resorted to the ATLAS default definitions.

In order to maximise  $S/\sqrt{B}$  we apply the following selection cuts (see [9] for details)

- (i) We demand one electron with  $p_T > 30$  GeV or a muon with  $p_T > 20$  GeV, and  $|\eta| < 2.5$  for both leptons.
- (ii) We veto events with two or more leptons with  $p_T > 10$  GeV. This cut eliminates the leptonic  $t\bar{t}$  background almost completely.
- (iii) We veto events with leptons having  $p_T$  above 55 GeV.
- (iv) Events with missing energy below 50 GeV are excluded. This is a cut that dramatically reduces the QCD background.
- (v) We ask for one and only one  $b$ -tagged jet with  $p_T < 75$  GeV. We assume a  $b$ -tagging efficiency of 0.4 (with  $R = 0.7$ ), while the misidentification rates for the case of  $c$ -quark jets we take 0.1 and for lightquark/ gluon jets we adopt 0.01.
- (vi) We reconstruct a "top quark invariant mass" as defined in [9] and demand all events to have this invariant mass above 280 GeV. The top quark invariant mass distribution for signal and background is shown in figure 1.
- (vii) We define a leptonic transverse mass [9],  $M_T^{l\nu}$ , and we have accepted events with  $30 \text{ GeV} < M_T^{l\nu} < 60 \text{ GeV}$  for charged Higgs masses between 90 and 130 GeV and  $30 \text{ GeV} < M_T^{l\nu} < 60 \text{ GeV}$  or  $M_T^{l\nu} > 85 \text{ GeV}$  for higher values of the charged Higgs mass. The leptonic transverse mass distribution for signal and background is shown in figure 1.
- (viii) We have chosen events with one and one jet (non- $b$ ) only with  $p_T > 30$  GeV and  $|\eta| \leq 4.9$ .
- (ix) We veto all events with a jet multiplicity equal to two or above for jets with  $p_T > 15$  GeV and  $|\eta| \leq 4.9$ .
- (x) We only accept events where jets have a pseudorapidity  $|\eta| \geq 2.5$ .

Putting all the numbers together we can find  $S/B$  and  $S/\sqrt{B}$  as a function of the charged Higgs mass as presented in table 1.

The results can be presented in a model independent manner as done in [9] and from them exclusion plots can be derived for the different 2HDMs. Before proceeding we present in the left



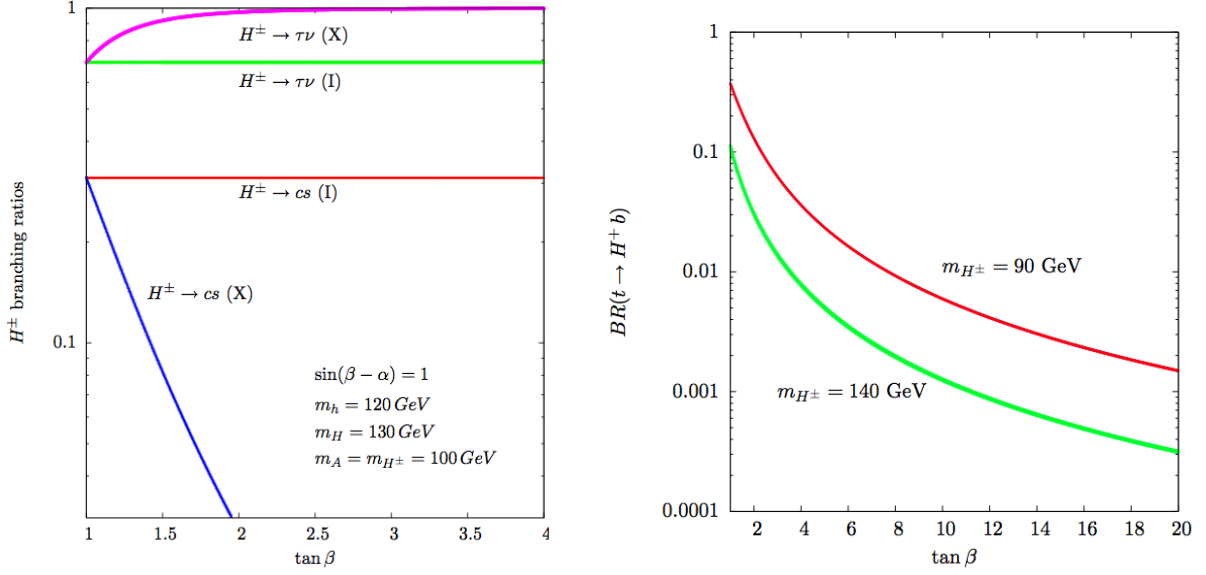
**Figure 1.** Left: "top quark invariant mass" distribution for signal and background. Right: leptonic transverse mass distribution for signal and background.

**Table 1.** Signal-to-Background ratio ( $S/B$ ) and significance ( $S/\sqrt{B}$ ) as a function of the charged Higgs mass for  $\sqrt{s} = 14$  TeV and a luminosity of  $1 \text{ fb}^{-1}$ . The numbers presented for the signal we take  $\text{BR}(t \rightarrow bH^\pm) = 100\%$  and  $\text{BR}(H^- \rightarrow \tau^- \nu) = 100\%$  and all other Branching Ratios (BRs) have the usual SM values.

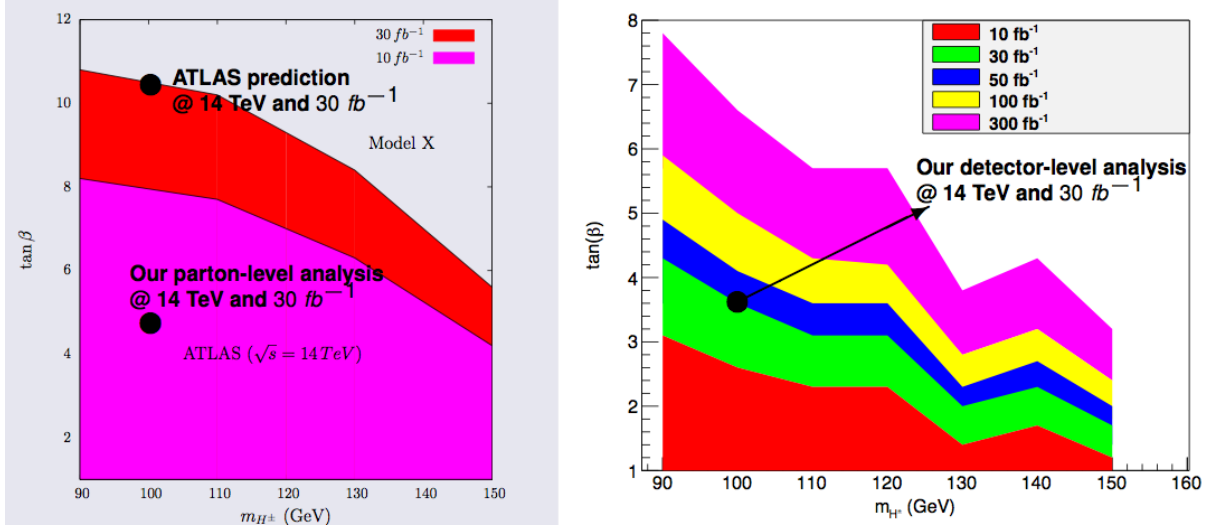
$m_H^\pm$ (GeV)	Signal ( $S$ )	Background ( $B$ )	$S/B$ (%)	$S/\sqrt{B}$
90	38.6	29.5	130.92	7.11
100	40.5	29.5	137.19	7.45
110	45.6	29.8	153.00	8.35
120	47.7	30.1	158.26	8.69
130	42.3	32.7	129.53	7.41
140	117.1	77.9	150.25	13.26
150	120.0	86.6	138.64	12.90
160	109.7	100.8	108.81	10.92

panel of figure 2 the charged Higgs BRs for  $m_{H^\pm} = 100$  GeV as a function  $\tan \beta$  in models Type I and X. Clearly  $H^+ \rightarrow \tau^+ \nu$  is the dominant decay mode in both models. As the charged Higgs boson width depends only on  $\tan \beta$  and on the charged Higgs mass, the plot is representative of all values of  $m_{H^\pm}$  provided that decays to other neutral scalars is forbidden. In the right panel of figure 2 we show the  $\text{BR}(t \rightarrow H^+ b)$  as a function of  $\tan \beta$  for two values of the charged Higgs boson mass. Contrary to the case of the MSSM and MSSM-like versions of a Type II 2HDM, this BR falls very rapidly with  $\tan \beta$  and even more so as the charged Higgs boson mass approaches the top-quark mass.

Using this information we can now draw exclusion plots for the different 2HDM types. In the left panel of figure 3 we present the excluded region at the 95% CL in the  $(\tan \beta, m_{H^\pm})$  plane for the Type X 2HDM model using the ATLAS predictions for  $10 \text{ fb}^{-1}$  and  $30 \text{ fb}^{-1}$  of total integrated luminosity for the LHC@14 TeV [19]. In the same figure we have drawn a point that corresponds to our parton level prediction for  $30 \text{ fb}^{-1}$  and  $m_{H^\pm} = 100$  GeV presented in [20]. In the right panel of the same figure we show the excluded region in the  $(\tan \beta, m_{H^\pm})$  plane for Type X at the 95% CL assuming the LHC@14 TeV and for several luminosity sets. The 100 GeV mass point at  $30 \text{ fb}^{-1}$  is also shown for a better comparison both with the ATLAS



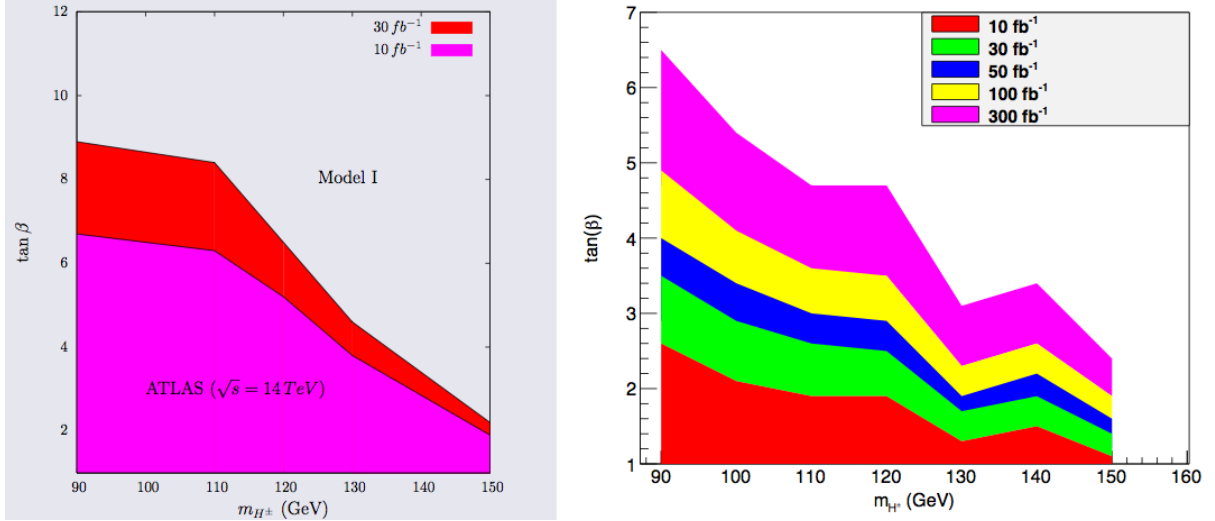
**Figure 2.** Left: charged Higgs BRs for  $m_{H^\pm} = 100$  GeV as a function of  $\tan\beta$  in models Type I and X. Right:  $BR(t \rightarrow H^+ b)$  as a function of  $\tan\beta$  for two values of the charged Higgs boson mass.



**Figure 3.** Left: Excluded region at the 95% CL in the  $(\tan\beta, m_{H^\pm})$  plane for the Type X 2HDM using the ATLAS predictions for  $10 \text{ fb}^{-1}$  and  $30 \text{ fb}^{-1}$  of total integrated luminosity for the LHC@14 TeV [19]. Also shown is our parton level prediction for  $30 \text{ fb}^{-1}$  [20]. Right: excluded region in the  $(\tan\beta, m_{H^\pm})$  plane for Type X at the 95% CL assuming the LHC@14 TeV and for several luminosity sets.

prediction and with our previous parton level study [20]. In the left panel of figure 4 we now present the excluded region for the Type I model again using the ATLAS predictions for  $10 \text{ fb}^{-1}$  and  $30 \text{ fb}^{-1}$  of total integrated luminosity for the LHC@14 TeV [19]. In the right panel we present our final detector level results for Type I at the 95% CL assuming the LHC@14 TeV and for several luminosity sets. We can conclude from the plots that as expected the results show

similar trends to the ones obtained for  $t\bar{t}$  production. We started with a cross section that is about three times smaller than the  $t\bar{t}$  one and ended up with a result that is 2 to 3 times worse than the prediction presented by ATLAS [19].



**Figure 4.** Left: excluded region at the 95% CL in the  $(\tan\beta, m_{H^\pm})$  plane for the Type I 2HDM model using the ATLAS predictions for 10  $\text{fb}^{-1}$  and 30  $\text{fb}^{-1}$  of total integrated luminosity for the LHC@14 TeV [19]. Right: excluded region in the  $(\tan\beta, m_{H^\pm})$  plane for Type I at the 95% CL assuming the LHC@14 TeV and for several luminosity sets.

It is expectable that both ATLAS and CMS will improve the results on the single top mode presented here, tightening the constraints on the  $(m_{H^\pm}, \tan\beta)$  plane. One may now ask what are the chances to probe the entire  $(m_{H^\pm}, \tan\beta)$  plane by the end of the 14 TeV run. In view of the results for 7 TeV [1, 2], one expects a type II light charged Higgs to be excluded by then. However, there are models where the Yukawa couplings always decrease with  $\tan\beta$  as is the case of models I and X. For those models, we know that  $pp \rightarrow t\bar{t}$  will provide the strongest constraint on the  $(m_{H^\pm}, \tan\beta)$  plane, and that the single top mode is bound to contribute even if only with a slight improvement. Are there any other processes that could help to probe the large  $\tan\beta$  region?

There is another Yukawa process,  $cs \rightarrow H^\pm(+j)$  [21, 20], that could in principle help to probe the above mentioned region. It was however shown to be negligible for large  $\tan\beta$ . The remaining possibility [20] is to look for processes that either do not depend on  $\tan\beta$ , or even better, that grow with  $\tan\beta$ . There are terms both in  $gg \rightarrow H^+W^-$  and in vector boson fusion ( $pp \rightarrow jjH^+H^-$  where  $j$  is a light quark jet) that are independent of  $\tan\beta$ . Furthermore, for the CP-conserving potential, there is a term in  $gg \rightarrow H^+H^-$  that has the form

$$\sigma_{pp \rightarrow H^+H^-} \propto \sin(2\alpha) \tan\beta (m_H^2 - M^2) \quad (1)$$

where  $\alpha$  is the rotation angle in the CP-even sector,  $m_H$  is the heavier CP-even scalar mass and  $M^2 = m_{12}^2/(\sin\beta \cos\beta)$ . Hence, there are regions of the 2HDM parameter space that can be probed for larger values of  $\tan\beta$ . However, the bounds will no longer be for a two parameter space but instead for a multi-dimension space with all 2HDM parameters playing a role. Further, values of the cross section that could lead to meaningful significances are only obtained for resonant production. Therefore, only a small portion of the multi-dimensional space can be probed for large  $\tan\beta$  (see [20] for details).

A final comment about theoretical bounds. Assuming that the Higgs boson was discovered with a mass of 125 GeV, it was recently shown in [22] that for the particular case of an exact CP-conserving  $Z_2$  symmetric model  $\tan\beta < 6$ . Therefore, that particular model will probably see a light charged Higgs ruled out when all the 8 TeV data is analysed.

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